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MAPPING OF GRADIENTS OF INDOOR TEMPERATURE, CO_2 AND PM_{10} THROUGH A MULTISENSORS OBSERVATIONAL CAMPAIGN

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Abstract: Indoor air pollution is one of the major problems affecting human health alongside outdoor pollution. Indoors the concentrations of pollutants are usually higher than outdoors as there is contamination from outdoors as well as sources of pollution coming from activities or materials used indoors. The COVID-19 pandemic exacerbated the need to properly assess the ventilation to improve indoor air quality and preserve health but this should be done while taking into account the energy consumption of HVAC systems (heating, ventilation and air conditioning). The HVAC systems may eventually be controlled to assess the needs of each different room, and this can be done through the installation of low-cost sensors, which can be placed in each room of the building. This work investigates whether it is possible to observe a spatial and temporal distribution of indoor pollutants using low-cost sensors through a measuring campaign in an office in Turin, Italy. The sensors were placed on some shelves at different heights and in various locations in the room. Scientific literature mainly assesses vertical profiles of pollutants in experimental chambers measured with high-grade sensors. The results show good agreement in the vertical profiles of CO_2 and PMs despite using low-cost sensors.

Key words: *Stratification of indoor air pollutants, Time and space distribution of indoor pollutants, Vertical profiles of indoor air pollutants, Low-cost sensors for mapping of indoor pollutants*

INTRODUCTION

Outdoor air pollution is one of the major problems that affects health in urban areas. However, people usually spend 80-90% of their time indoors (ASHRAE, 2010), where they study, work, sleep, cook and spend time with their families. Despite feeling safer indoors, the concentration of indoor air pollutants is often twice to five times higher than outdoors, resulting in higher cumulative exposure and therefore potential health effects in both the short and long term. Historically, the research on air quality was mainly conducted on outdoor air (Sundell, 2004), however, in the last decades there has been an increasing focus on indoors, where air can be significantly more polluted than outdoors (EPA, 2013). This trend was further exacerbated by the COVID-19 pandemic when it became clear also to non-expert people that indoor air quality is important for their health and that improving ventilation can reduce the spread of airborne diseases as well as reduce health effects due to high concentrations of contaminants.

Nowadays, many buildings are equipped with HVAC systems (Heating, Ventilation and Air Conditioning), which are used for heating, cooling and improving air exchange. However, HVAC systems can account for 60-70% of the energy consumption of the buildings (Pérez-Lombard, 2008). Therefore, it is crucial to control them appropriately to save energy while maintaining good indoor air quality so as not to affect the health of the occupants. Indeed, to save energy it is necessary to reduce the flow rate and the working time of the HVAC system, however, this may not guarantee the appropriate mixing and air exchange rate.

Some sensors can be installed to monitor the thermal conditions and pollutant concentration indoors and thus adjust the ventilation optimally to preserve both energy and the occupants' health. However, some studies confirm that it is possible to observe a space distribution of pollutants even in an indoor environment (e.g. Zhang, 2006). Therefore, it is important to choose the correct position for the sensors. This can be done in two ways: the first is to simulate the evolution of the pollutants in the room using CFD (Computational Fluid Dynamics) models (e.g. Gao, 2007) and the other is to conduct a campaign that employs indoor air quality sensors at different heights and in different places of some indoor environments. The usage of CFD to predict the concentrations of indoor air pollutants is widely spread (Shree, 2019); however, the models may be inaccurate in some cases as it is still unknown how some variations in space are affected by the emitting sources (Mahyuddin, 2010). On the other hand, the investigation of the spatial distribution of indoor pollutants using observational campaigns is not properly addressed in literature sources, mainly due to the experimental costs of the sensors (Mahyuddin, 2010). Few monitoring investigations were conducted in a strictly controlled environment (e.g. Zhang, 2006) and these data were used to validate new CFD models or to investigate PM distributions (e.g. Patel, 2017). However, in recent years many low-cost sensors have been developed and their great improvements may be a great opportunity to conduct experiments with lower budgets (Dai, 2023).

In this work, we present an investigation of indoor air pollutants spatial distribution in a closed, work office environment when it was empty. The present study was conducted with the usage of 30 low-cost air quality multisensors positioned at different heights and locations within the room.

EXPERIMENTAL SETUP

The campaign lasted from the 12th of April to the 6th of May and it was conducted by installing 30, low-cost multisensors in an office located on the second floor of a newly constructed building in Turin, Northern Italy. The office has a window that faces a street, located around 40 cm above the floor, where road traffic is low, and it is separated from the corridor by a transparent glass wall. The ventilation, heating and cooling are achieved through an HVAC system, which operates daily from 6:00 to 17:00 UTC on weekdays and from 7:00 to 11:00 UTC on Saturday mornings, while it is switched off in the remaining timeframes. There are two supply air vents, which are located on the ceiling near the corridor, while the two recovery air vents are placed on the ceiling beside the window. A floor plan and a picture of the room are shown in Figure 1 (left and right panels respectively).

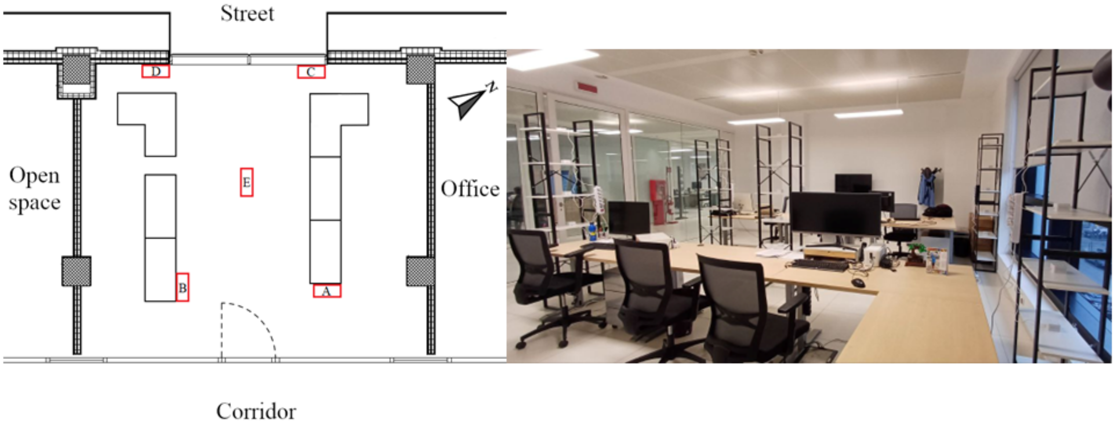

Figure 1. Left: Office floor plan with desks (black rectangles) and shelves (red rectangles). Right: picture of the room showing the shelves and multisensors set up.

The 30 multisensors provide the concentrations of indoor air pollutants (CO_2, PM_1, $PM_{2.5}$, PM_{10}, VOCs) as well as the measurements of temperature, atmospheric and sound pressures, relative humidity and illuminance every five minutes. It is worth mentioning that for the VOCs component, instead of the actual concentration, the multisensors provide an index, which takes into account their concentrations during the previous 24 hours. The technical characteristics of the multisensors are summarised in Table 1.

Table 1. Range and resolution of the measured quantities provided by the multisensors.

Quantity	Unit	Range	Resolution
Temperature	°C	(-40.0 to 85.0) °C	0.1°C
Relative humidity	RH%	(0.0 to 100.0) RH%	0.1 RH%
Atmospheric pressure	hPa	(300.00 to 1100.00) hPa	0.01 hPa
CO_2	ppm	(0 to 5000) ppm	1 ppm
PM_1, $PM_{2.5}$, PM_{10}	$\mu g\ m^{-3}$	(0 to 2000) $\mu g\ m^{-3}$	1 $\mu g\ m^{-3}$
VOC	VOC index	(0 to 500)	1
Sound pressure	dB(A)	(30.0 to 120.0) dB(A)	0.5 dB(A)
Illuminance	lx	(0 to 120000) lx	1 lx

The multisensors were placed on five different shelves, which were distributed as shown in Figure 1; two shelves by the window (shelves C and D), two by the corridor (shelves A and B) and the last one in the centre of the room (shelve E). Each shelf allocated six different multisensors at the heights of 20.5 cm, 55.2 cm, 90.2 cm, 125.1 cm, 160.1 cm and 195.4 cm above the floor. Unfortunately, the multisensor located at 160.1 cm on shelf E in the centre of the room failed to collect the concentrations of PMs, and the multisensor located at 20.5 cm on shelf D beside the window stopped working at 14:30 UTC on the 18th of April. The data analysed in the present article covered only the first ten days of the campaign, from the 12th to the 22nd of April. The analysis of the complete set of data will be available in Racca et al., 2025.

RESULTS

To better compare the results of the measurements taken during the campaign with the results obtained in the strictly controlled environments and inspect whether it is possible to observe stratification phenomena, it was decided to analyse first the data collected during the weekend and nights. Indeed, during these periods the HVAC system was not active (except on Saturday morning), and there were no occupants. The average of the concentrations of air pollutants at the same height was considered for the analysis presented in this work, to investigate the vertical profile of the concentrations and potentially stratification effects.

This analysis focused on the behaviour of PMs, CO_2 and temperature. The VOCs were excluded due to the lack of a clear connection between their concentrations and the index provided by the multisensors.

PMs and CO_2 observation

During most nights and weekends, the average concentrations of PMs (1.3 $\mu g\ m^{-3}$) were close to the resolution of the instrument, therefore these periods were discarded for the analysis because data may not be accurate enough. Figure 2 (bottom panel) reports the behaviour of PM_{10} concentration for the night between the 15th and 16th of April, during which it was three times higher than the resolution, due to a peak of concentration during the day. From the figure, it can be observed that after an initial phase during which the average values are comparable at different heights, starting from 21:30 UTC the higher values of PM_{10} are reported at 20.5 cm, while lower values were recorded above 50 cm. The highest concentrations at 20.5 cm were recorded by shelves near the window (shelves D and C, Figure 1). Similar results were reported in the work of Zhang (2006), in which peaks of air pollutant concentrations were reported at a height between 20 and 50 cm above the ground for active sources located 30 cm above the floor, reaching almost flat values at heights higher than 50 cm.

The top panel of Figure 2 reports the corresponding behaviour for CO_2 during the same period. As can be seen, the concentrations overall decrease due to the lack of CO_2 sources during the night, ranging from 510 ppm when the HVAC stopped working to 425 ppm right before the HVAC system is reactivated. Indeed, CO_2 is mainly produced by humans, who are not present at night in the office; therefore draughts from the window may contribute to decreasing CO_2 concentrations closer to external concentration values. In general, higher values of CO_2 concentrations are measured at low heights.

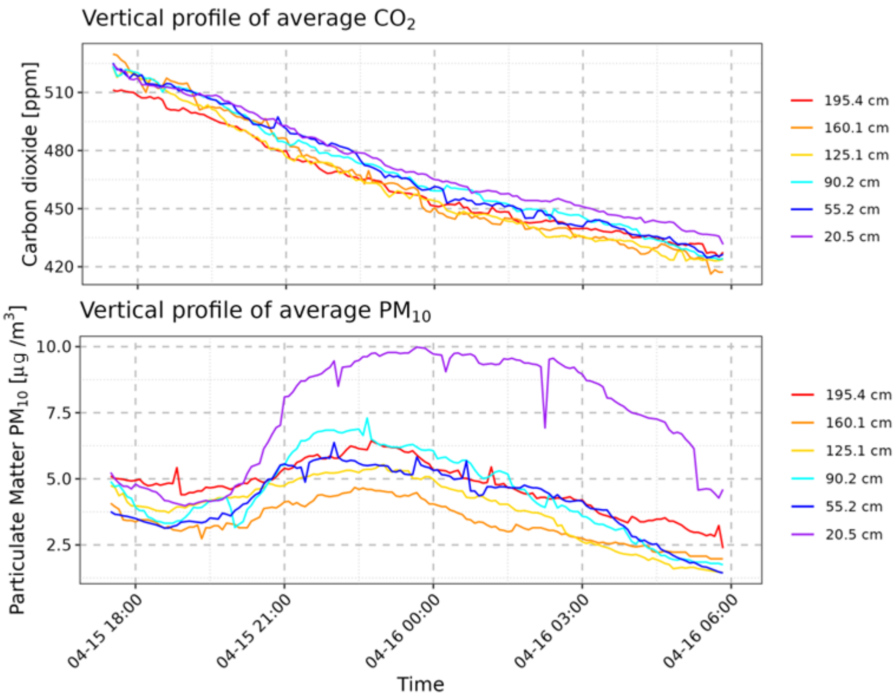

Figure 2. Behaviour of the average values of CO_2 (top panel) and PM_{10} (bottom panel) concentrations for the night between the 15th and the 16th of April. The different coloured lines refer to the different heights on the shelves.

Temperature

Figure 3 shows the behaviour of the temperature at different heights for the period going from the 12th to the 22nd of April. The temperature ranges in the room between 10 and 30 °C, with a typical profile increasing with the height. During the day, the temperature takes values increasing monotonically with the height, while during the night the values are mixed for sensors located above 55.2 cm, with the lowest temperature recorded by the sensors at the bottom of the shelves. The diurnal temperature profile is expected due to the heating and ventilation system located at the ceiling of the room, while during the night the behaviour results mixed due to the absence of any heating source.

The thermal profile can help investigate the behaviour observed by PMs, since lower values of temperature at the bottom of the shelves may inhibit possible convection motion, making PMs and CO_2 stagnate at lower heights.

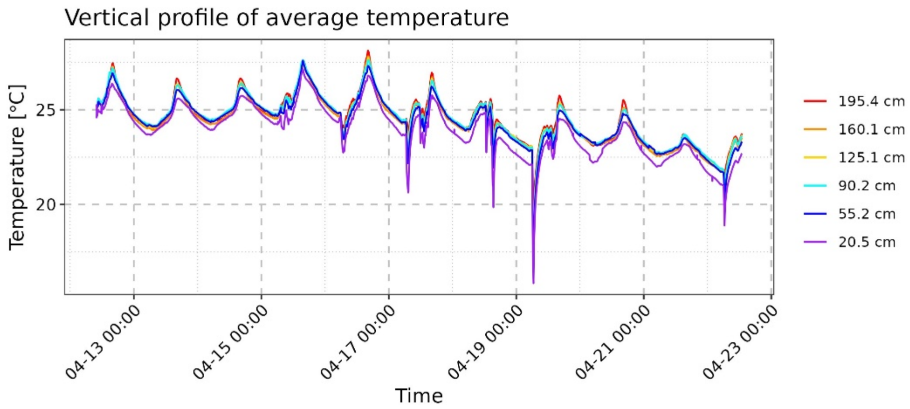

Figure 3. Behaviour of the average values of temperature for the campaign period from the 12th to the 22nd of April. The different coloured lines refer to different heights on the shelves.

CONCLUSIONS

This work investigated the possibility of mapping indoor air pollutant concentrations using low-cost sensors, that may represent a good alternative to reduce the costs of the experiments while increasing measuring points. For the measuring campaign, which lasted from the 12th of April to the 6th of May, the 30 multisensors used were placed at six different heights and in five locations inside an office in Turin, Italy. The vertical profiles of the PMs during the night between the 15th and the 16th of April show that a higher concentration may be observed at around 20 cm above the floor, which is in good agreement with the behaviour reported by previous works in a controlled chamber. CO_2 concentration typically decreases throughout the night since there is no CO_2 source indoors, and any window drafts may help bring the levels closer to those outside. The temperature exhibits a profile, which shows that higher values were recorded by the multisensors positioned in higher places. During the nights colder temperatures on the lower shelves may reduce the convection and therefore inhibit the buoyancy of pollutants. The results of this work report an overall qualitative agreement between literature results in experiments in controlled environments and in real time monitoring in daily occupied working offices, making low-cost sensors a relatively cheap alternative to set up monitoring experiments of indoor air pollutants distribution. Future developments of this work will involve the analysis of the vertical profiles of the pollutants during the day, where the occupants' behaviour may affect the possible stratification.

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